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Measuring the coordinated development of the advanced manufacturing cluster based on patent data: A composite system approach

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A B S T R A C T

The advanced manufacturing industry serves as a key driver of high-quality economic development, with patent data widely used to assess regional technological innovation and synergy. Evaluating coordination within advanced industrial clusters offers practical insights into industrial upgrading. Focusing on the Beijing–Tianjin–Hebei advanced manufacturing cluster in China, the composite system is divided into four subsystems: quantity, quality, efficiency, and value. Using patent data from 2013 to 2023, a composite system synergy model was built to measure the degree of synergy. A coupling coordination degree model and an obstacle degree model were applied together to examine coordination states and limiting factors. The findings show a generally rising synergy degree in the cluster, indicating increased organizational coherence over time. Coupling coordination displayed short-term fluctuations but exhibited a positive long-term trend, achieving high-quality coupling by 2023. Collaborative development is dynamically influenced by multidimensional obstacles, calling for timely and tailored measures to improve synergy efficiency. This study offers an empirical basis for optimizing collaboration in the Beijing–Tianjin–Hebei cluster and provides a theoretical reference for understanding synergy mechanisms in similar industrial clusters.

A R T I C L E I N F O

Keywords:
Advanced manufacturing cluster;
Patent data;
Composite system synergy;
Coupling coordination degree;
Obstacle degree;
Regional industrial coordination;
Innovation synergy

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1. Introduction

Driven by breakthroughs and integration in information technology, automation, and related fields, the manufacturing industry is undergoing a profound shift toward intelligent, green, and service-oriented development [1]. To secure future industrial leadership, countries have launched supportive policies such as the U.S. “re-industrialization” strategy, Germany’s “Industry 4.0”, and China’s “Made in China 2025”. A central aim is to cultivate globally competitive advanced manufacturing clusters that integrate innovative resources and enhance overall industrial efficiency [2,3]. However, differences in resource endowments and development stages among entities within a cluster often lead to insufficient systemic coordination, limiting further competitiveness gains [4,5]. Scientifically diagnosing the synergy status and identifying key obstacles thus becomes essential to promote high-quality cluster development [6].

In order to objectively describe the synergy level of the cluster system, this study introduces patent data as the core observation index. As the key carrier of the legalization and marketization of technological achievements, patent has become an important indicator for measuring the progress of technological innovation and the advanced manufacturing industry because of its objectivity and quantifiable characteristics, which provides a scientific perspective for insight into the collaborative innovation efficiency of regional industrial clusters.

Against the global backdrop of patent-driven innovation, the Beijing–Tianjin–Hebei advanced manufacturing cluster is examined as a composite system. By constructing a synergy measurement model, the development synchronization and synergy degree of the composite system are quantitatively evaluated [7]. This approach helps reveal dynamic patterns and key obstacles in the cluster's coordinated development, offering both empirical support for strategic decision-making in the Beijing–Tianjin–Hebei region and a theoretical and practical reference for similar industrial clusters worldwide to optimize resource allocation and improve collaborative innovation efficiency.

2. Literature review

2.1 Coordinated development approach

In terms of measuring the overall synergy of the system, there are many methodological paths, mainly including the DEA method, distance synergy model, Haken model, composite system synergy model, coupling coordination degree, among others. Khare *et al*. [8] used the DEA model to quantitatively evaluate the synergistic relationship between bus rapid transit system and land use under 16 public transit-oriented development models in Bhopal, India.

Li *et al*. [9] used the distance synergy model to quantitatively analyse the panel data of Beijing-Tianjin-Hebei from 1995 to 2014, reflecting the regional coordinated development. Luo and He [10] combined the similarity measure of the Vague set with the distance collaborative model, used the grey correlation analysis to calculate the grey correlation degree between the supply and demand subsystems, and established a comprehensive collaborative development model of regional high-tech industry technology supply and demand composite system based on Vague set distance and grey correlation.

Ouyang and Yang [11] constructed a new measurement method of regional coordinated development based on the Haken model and simultaneously constructed an index system to examine the situation of regional coordinated development in China from five dimensions. Based on the panel data of 13 cities from 2003 to 2020, Deng *et al*. [12] established an evaluation index system for high-quality economic development of Beijing–Tianjin–Hebei urban agglomeration, and used the spatial Durbin model to examine the impact of collaborative innovation on high-quality economic development.

Leydesdorff and Fritsch [13] used the three sub-powers of economic exchange, technological innovation and institutional control to construct a triple helix model to measure the level of collaborative innovation in German manufacturing. Fang *et al*. [14] measured the performance level of coordinated development in a certain region, and found that the level of coordinated development in the region showed a slow growth trend over time.

Zhao and Zhang [15] used the composite system synergy model to measure the ecological synergy level of Beijing, Tianjin and Hebei, and found that the level of ecological synergy development in Beijing, Tianjin and Hebei increased year by year, but the development of subsystems within the region was uneven. Sun *et al*. [16] used the order degree model and the composite system synergy model to measure both the subsystem order degree and the composite system synergy degree of CSHDME, based on the data of 11 coastal provinces in China from 2010 to 2020.

Based on the coordination degree model of composite system, Shen *et al*. [17] constructed the coordination degree model of aviation logistics industry in Beijing–Tianjin–Hebei region, and analysed the ordered variables reflecting the development of aviation logistics industry in the region from 2005 to 2014, and dynamically depicted its collaborative evolution process. Ren *et al*. [18] constructed a four-level comprehensive evaluation index system based on the DPSIR framework, used the entropy weight method to determine the index weight, and used the coupling coordination degree model to analyse the coordination relationship between the systems.

Xu and Shi [19] constructed an evaluation index system including four major industrial subsystems such as network economy, and used the coupling coordination degree model to statically measure the level of collaborative innovation of strategic emerging industries in China and provinces from 2012 to 2022. Zheng and Gu [20] divided the Beijing–Tianjin–Hebei carbon emission reduction system into four subsystems such as policy support. Based on the synergy degree of the composite system, the coupling coordination degree model was used to analyse the synergistic governance effect of regional carbon emissions.

2.2 Analysis model of influencing factors

At present, the academic research on the analysis methods of influencing factors is not uniform, mainly including the DEMATEL method, factor analysis, principal component analysis, obstacle degree model and so on. Shi *et al*. [21] used the DEMATEL method to identify 11 key risk factors from the perspective of causality, and revealed the differences between causal factors and outcome factors by analysing their centrality and causality.

Kang *et al*. [22] used geographical detector to conduct factor analysis, and found that natural factors dominated the spatial and temporal distribution of GPP in a province. Hou *et al*. [23] used the grey correlation model to comprehensively evaluate the quality of medicinal materials by calculating the relative correlation between each batch of samples and the optimal reference sequence.

Some researchers used structural equation modeling to investigate household tourism consumption, and discussed the influencing factors of potential variables, such as income structure, household and regional characteristics of consumption structure [24, 25]. Gao *et al*. [26] used the principal component analysis method to reduce the dimension of the five dimensions of production efficiency, overall prosperity, coordinated development, achievement sharing and ecological welfare, so as to extract the main factors affecting common prosperity.

Yang *et al*. [27] used the obstacle degree model to identify the main obstacle factors affecting the coordinated development of the regional innovation environment-resource-output-benefit composite system by calculating the product of the deviation degree and weight of each index, so as to provide a basis for policy optimization. Wang *et al*. [28] used the obstacle degree model to identify the main obstacle dimensions affecting the development of new quality productivity of water conservancy, among which the high-tech dimension had the largest obstacle, followed by high-quality, green and efficient dimensions [29].

2.3 Synthesis and research gap

Existing research offers a diverse methodological foundation for assessing coordinated development. However, integration between dynamic and static analysis remains limited, with most studies focusing on level evaluation rather than diagnosing development bottlenecks. To address this, a tiered analytical framework is constructed. First, the synergy degree of the composite system and the coupling coordination degree are comprehensively applied to reveal the coordinated development mechanism of the Beijing–Tianjin–Hebei advanced manufacturing cluster from a combined dynamic-static perspective. Then, compared with other approaches, the obstacle degree model is introduced to more accurately quantify key constraints on coordination. This framework provides a clear basis for formulating targeted governance strategies.

3. Methodology

Based on the constructed index system and weights determined by the coefficient of variation method, the system coordination level is first measured using the composite system synergy degree model. These results then serve as direct input into the coupling coordination degree model to evaluate the system's overall coordination state. Finally, key constraints are identified through the obstacle degree model, thereby completing a full analytical cycle from diagnosis to solution. Method Framework is shown in Fig. 1.

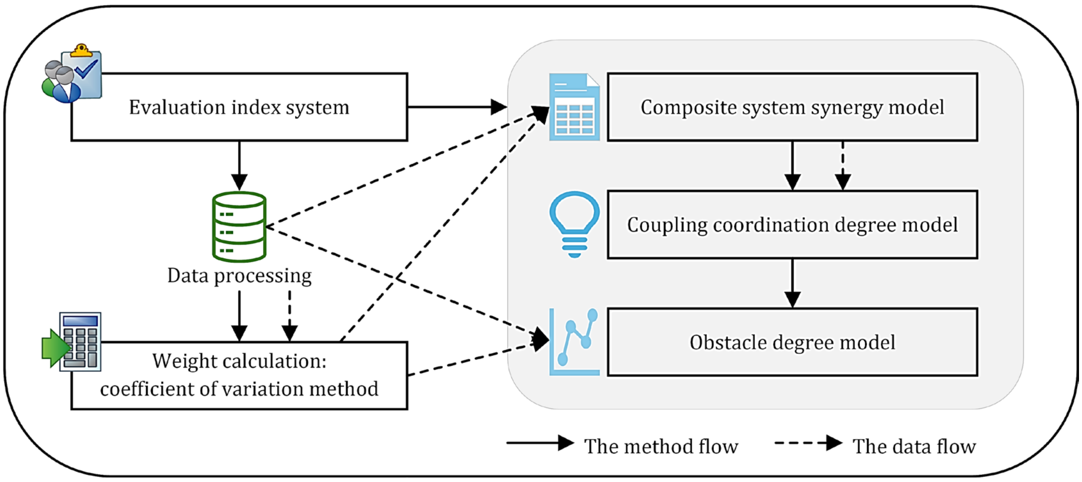

Fig. 1 Methodological framework

3.1 Evaluation index system construction

The coordinated development process of Beijing–Tianjin–Hebei advanced manufacturing cluster can be regarded as a complex system. In order to comprehensively and objectively reflect the coordinated development of the industrial cluster, on the basis of the availability of advanced manufacturing data, constructs the quantity, quality, efficiency and value as the four subsystems of the coordinated development of the cluster, and selects the order parameters that can reflect the dominant role of each subsystem, and constructs the evaluation index system of the synergy degree of the composite system of the coordinated development of the cluster, which is shown in Table 1.

Table 1 Evaluation index system for the coordinated development of the advanced manufacturing cluster

Subsystem	Numbering	Order parameter	Attribute
Quantity	A1	Quality requested	Positive
	A2	Growth of invention patent applications	Positive
	A3	Authorized amount	Positive
	A4	Invention patent authorization	Positive
Quality	B1	The average number of families	Positive
	B2	Average number of weights	Positive
	B3	Average number of IPC categories	Positive
	B4	The average number of the same family of invention patents	Positive
	B5	The average number of invention patent rights	Positive
	B6	The average IPC classification number of invention patents	Positive
Efficiency	C1	Average review duration	Negative
	C2	The average examination time of invention patents	Negative
	C3	The proportion of review duration meeting the threshold value	Positive
	C4	The proportion of invention patent examination time meeting the threshold value	Positive
Value	D1	Average annual DPI patent comprehensive value	Positive
	D2	Average annual DPI patent comprehensive value of invention patents	Positive

3.2 Data sources and processing

Data processing primarily involves retrieving, downloading, deleting duplicates, filtering, and merging data. The data processing flowchart is shown in Fig. 2. Patents were searched using the Dawei Innojoy patent search engine, yielding 180,689 results. Duplicates were then deleted, retaining the latest by disclosure time, resulting in 152,168 patents. Subsequently, data were filtered based on conditions including application year, authorization year, and legal status announcements indicating dismissal or withdrawal, with the filtering period set to 2013-2023. Finally, data merging produced a valid dataset of 146,765 patents.

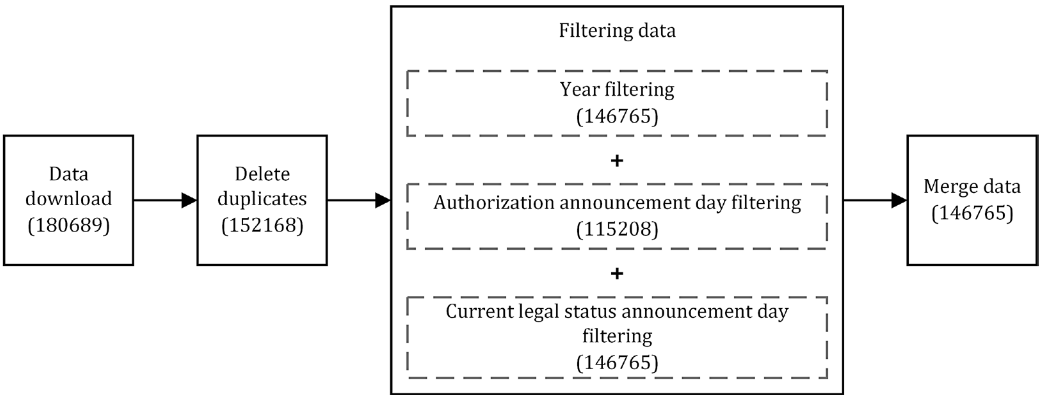

Fig. 2 Data processing flowchart

3.3 Evaluation index weight calculation

The weight of evaluation indexes significantly impacts overall evaluation outcomes. Empowerment is achieved using the coefficient of variation (CV) method, a statistical approach measuring data dispersion through index CV values. Higher CV values correspond to greater weights. Calculation steps follow:

(1) Raw data collection: Suppose that there are m indicators in a set of data, n samples to be evaluated, that is, an $n * m$ matrix, let it be X. Where x_{ij} denotes the data of row i and column j.

$$X = \begin{pmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{pmatrix} \tag{1}$$

(2) Positive index data: convert all indicators into positive index (that is, the larger the value, the better).

For the positive index, keep its original data unchanged:

$$x'_{ij} = x_{ij} \tag{2}$$

For the negative index, the following methods are used:

$$x'_{ij} = \frac{1}{k + max|x_j| + x_{ij}} \tag{3}$$

(3) Data standardization: its purpose is to eliminate the influence of the unit, so that all data can be calculated in the same way. The normalized data matrix is R:

$$r_{ij} = \frac{x'_{ij}}{\sqrt{\sum_{i=1}^{n} x'^2_{ij}}} \tag{4}$$

(4) Calculate the coefficient of variation: Eqs. 5 to 7 are the calculation of the mean, standard deviation (mean square error) and coefficient of variation of each index.

$$A_j = \frac{1}{n}\sum_{i=1}^{n} r_{ij} \tag{5}$$

$$S_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(r_{ij} - A_j)^2} \tag{6}$$

$$V_j = \frac{S_j}{A_j} \tag{7}$$

(5) Calculate the weight:

$$w_j = \frac{V_j}{\sum_{j=1}^{n} V_j} \tag{8}$$

3.4 Composite system coordination degree

3.4.1 Subsystem order degree measurement model

A composite system S for Beijing–Tianjin–Hebei advanced manufacturing cluster coordinated development is established. This system comprises n subsystems, denoted as $S_i(i = 1, 2, \ldots., n)$. For each subsystem S_i, the order parameter $S_{ij}(j = 1, 2, \ldots, m;\ m \geq 1)$ is defined, where m represents the number of order parameters. The lower and upper bounds of S_{ij} are α_{ij} and β_{ij} respectively, with $\alpha_{ij} \leq S_{ij} \leq \beta_{ij}$. Based on composite system synergy degree theory, the order parameter order degree is calculated as follows:

$$\mu_i(S_{ij}) = \begin{cases} \dfrac{S_{ij} - \alpha_{ij}}{\beta_{ij} - \alpha_{ij}}, j \in [1, k] \\ \dfrac{\beta_{ij} - S_{ij}}{\beta_{ij} - \alpha_{ij}}, j \in [k + 1, m] \end{cases} \tag{9}$$

In the equation, the order parameters $S_{i1}, S_{i2}, \ldots, S_{ik}$ are positive indicators. The larger the value, the higher the order degree of the subsystem, where $k_i \epsilon\ [1, m_i]$; the order parameters $S_{ik+1}, S_{ik+2}, \ldots, S_{im}$ are negative indicators. The smaller the value is, the lower the order degree of the subsystem is $\mu_{ij} \epsilon\ [0, 1]$, and the larger the value, the greater the contribution of the order parameter S_{ij} to the subsystem.

The contribution of each order parameter S_{ij} to the subsystem is also related to its combination form and their respective weights. The linear weighted average method (LWA, Eq. 10) and geometric average method (GA, Eq. 11) are used to calculate the order degree $\mu_i(S_{ij})$ of the subsystem.

$$\mu_i(S_i) = \sum_{j=1}^{m} w_{ij}\, \mu_{ij}(S_{ij}), w_{ij} \geq 0 \wedge \sum_{j=1}^{m} w_{ij} = 1, \forall i \in (1, 2, \cdots, n) \tag{10}$$

$$\mu_i(S_i) = \sqrt[n]{\prod_{j=1}^{m} \mu_i(S_{ij})} \tag{11}$$

In the equation $\mu_i(S_i) \epsilon\ [0, 1]$, and the larger the value, the higher the order degree of the subsystem S_i, and vice versa. w_{ij} represents the weight of the order parameter S_{ij} in its subsystems, which can be obtained by the coefficient of variation method.

3.4.2 Composite system synergy model

Assuming that at a given initial time t^0, the order degree of the subsystems of the advanced manufacturing cluster collaborative development composite system is ${\mu_i}^0(S_i)$, respectively. At another time t^1 in the collaborative development process, the order degree of each subsystem is ${\mu_i}^1(S_i)$, respectively, where, $i = 1, 2, \ldots, n$. Through the linear weighted average method and the geometric average method, the synergy degree of the advanced manufacturing cluster collaborative development composite system in the region can be calculated as follows:

$$D = \theta \sum_{i=1}^{n} w_i \left[\left| \mu_i^1(S_i) - \mu_i^0(S_i) \right| \right], w_{ij} \geq 0 \wedge \sum_{i=1}^{n} w_i = 1 \tag{12}$$

$$D = \theta \sqrt[n]{\prod_{i=1}^{n} \left| \mu_i^1(S_i) - \mu_i^0(S_i) \right|} \tag{13}$$

In Eq. 13, $\theta = \frac{min_i[\mu_i^1(S_i) - \mu_i^0(S_i) \neq 0]}{|min_i[\mu_i^1(S_i) - \mu_i^0(S_i) \neq 0]|}$, ω_i represents the weight of the subsystem, which can be obtained by the coefficient of variation method.

The value of the synergy degree D of the composite system can directly reflect the synergy degree of the composite system. It can be seen from the above equation that the larger the value of D, the higher the synergy degree of the composite system. The parameter θ is used to determine the stability of the synergy degree of the composite system. When $\theta = 1$, the synergy degree D is positive, indicating that the development of advanced manufacturing cluster in the region is in a coordinated and orderly development stage. The larger the value is, the higher the synergy degree of the system is. When $\theta = -1$, the degree of synergy D is negative, which means that the advanced manufacturing cluster in the region has not achieved coordinated development.

3.5 Coupling coordination degree model

The coupling degree refers to the dynamic relationship of mutual influence between multiple systems or elements. The coupling coordination degree is formed based on this relationship and is used to analyse the coordinated development level of things. The calculation method is as follows:

$$D = \sqrt{C \times T} \tag{14}$$

$$C(U_1, U_2, \cdots, U_n) = n \times \left[\frac{U_1 U_2 \cdots U_n}{(U_1 + U_2 + \cdots + U_n)^n}\right]^{\frac{1}{n}} \tag{15}$$

$$T = w_1 U_1 + w_2 U_2 + \cdots + w_n U_n \tag{16}$$

In the equation, D is the coupling coordination degree; c is the coupling degree; t is the comprehensive evaluation value; $U_1, U_2, \ldots U_n$ are the internal coordination degree of each region; $w_1, w_2 \ldots, w_n$ are weights. The coordinated development of Beijing, Tianjin and Hebei affects each other and has the same status. Therefore, $w_1 = w_2 = w_3 = \frac{1}{3}$ in the three systems and $w_1 = w_2 = \frac{1}{2}$ in the two systems.

3.6 Obstacle degree model

In order to explore the factors that hinder the coordinated development of advanced manufacturing cluster in Beijing–Tianjin–Hebei, after evaluating its synergy level, the obstacle degree model is introduced. Taking 16 indicators in the evaluation system as obstacle factors, the obstacle degree of each index is calculated, and the main reasons that restrict the improvement of synergy degree are analysed, which lays a foundation for putting forward the guarantee mechanism. The specific steps are as follows:

$$O_{ij} = \frac{w_j \times (1 - r_{ij})}{\sum_{j=1}^{m} w_j \times (1 - r_{ij})} \tag{17}$$

In Eq. 17, w_j is the index weight of the j-th index to the synergy of advanced manufacturing cluster, $m = 16$ is the total number of evaluation indexes, r_{ij} is the index value of the j-th index in the i-th year after standardization, where the standardization processing adopts the above Eq. 4, $(1 - r_{ij})$ represents the gap between the j-th index and the ideal value in the i-th year, and O_{ij} represents the influence degree of the j-th index on the synergy of advanced manufacturing cluster in Beijing–Tianjin–Hebei region in the i-th year. The greater the O_{ij}, the higher the degree of hindrance to the coordinated development.

4. Authentic proof analysis

4.1 Weight

The importance of each index in the comprehensive evaluation can be scientifically determined by analysing the relative variation degree through the coefficient of variation method. Based on the calculation results of the coefficient of variation, the weight of each index is assigned as follows.

Table 2 Weight of indicators

Subsystem	Numbering	Order parameter weight	Subsystem weight	
			LWA	GA
Quantity	A1	0.2304	0.2835	0.2988
	A2	0.2403		
	A3	0.2527		
	A4	0.2765		
Quality	B1	0.0785	0.1204	0.1186
	B2	0.2162		
	B3	0.1860		
	B4	0.1172		
	B5	0.2225		
	B6	0.1795		
Efficiency	C1	0.0676	0.2177	0.2046
	C2	0.0611		
	C3	0.2411		
	C4	0.6302		
Value	D1	0.5560	0.3785	0.3780
	D2	0.4440		

4.2 Coordinated development of Beijing–Tianjin–Hebei advanced manufacturing cluster

4.2.1 Composite system synergy model

The maximum value of each order parameter from 2013 to 2023 is increased by 10 %, and the minimum value is reduced by 10 %, so as to determine the upper and lower limits of the order parameters. Then, the linear weighted average method and the geometric average method are used to calculate the order degree of the subsystem and the synergy degree of the composite system respectively.

Linear weighted average method

The linear weighted average method is a method of calculating the average value after giving different weights to different data points. It considers the difference of the overall contribution of each data point. The advantage of this method is that it can be adjusted according to the importance of the data. Subjectivity in the weight calculation process is eliminated by using the coefficient of variation method to calculate the order parameter weight.

Substituting the patent data and weights of the advanced manufacturing cluster in the Beijing–Tianjin–Hebei region into Eq. 10 and Eq. 12, the order degree of the Beijing–Tianjin–Hebei subsystem and the synergy degree of the composite system are shown in Table 3.

According to the data of Table 3, although the subsystem order degree of the Beijing–Tianjin–Hebei cluster fluctuates in some years, the overall trend shows a gradual upward trend, reflecting the overall progress of the Beijing–Tianjin–Hebei advanced manufacturing cluster. Overall, in the comparison of the same base period, the overall synergy degree of the cluster shows an overall upward trend from 2013 to 2023, which shows that in the long run, its development level continues to improve, and the overall synergy development ability continues to increase. In the comparison of adjacent base periods, the synergy degree shows a trend of fluctuating development, which indicates that the synergy effect or cooperation level between subsystems has changed in a continuous period of time.

Table 3 The subsystem order degree and composite system synergy degree of linear weighted average method

Year	Subsystem order degree				Composite system coordination degree	
	Quantity	Quality	Efficiency	Value	Same base period	Adjacent base period
2013	0.3420	0.3640	0.2120	0.0137	-	-
2014	0.3779	0.4033	0.2051	0.0238	-0.0202	-0.0202
2015	0.4508	0.3974	0.1913	0.0557	-0.0553	-0.0365
2016	0.4836	0.4094	0.1848	0.0737	-0.0742	-0.0190
2017	0.4637	0.4023	0.1295	0.0945	-0.0877	-0.0264
2018	0.5276	0.4149	0.1692	0.1130	-0.1056	0.0353
2019	0.5892	0.4949	0.2100	0.1453	-0.1361	0.0482
2020	0.7603	0.5496	0.3250	0.1993	0.2358	0.1006
2021	0.8118	0.6060	0.4391	0.2739	0.3103	0.0745
2022	0.8330	0.6079	0.6708	0.4244	0.4239	0.1136
2023	0.8218	0.6337	0.8220	0.8413	0.6145	-0.1970

Geometric average method

The geometric average method is to calculate the average value by multiplying all data points and opening the corresponding root mean square, which is suitable for processing data with ratio or exponential growth. The advantage of the geometric mean method is that it is not sensitive to extreme values and is suitable for processing proportional data, but the disadvantage is that it cannot be used when there are zero or negative numbers in the data points.

Substituting the patent data and various weights of the advanced manufacturing cluster in the Beijing-Tianjin-Hebei region into Eq. 11 and Eq. 13, the order degree of the Beijing–Tianjin–Hebei subsystem and the synergy degree of the composite system are shown in Table 4.

According to the data of Table 4, the trend of the synergy degree of the composite system calculated by the geometric average method is basically the same as that of the linear weighted average method. Compared with 2013, the order degree of each subsystem is improved as a whole, and the coordination degree of the same base period shows a significant upward trend, which indicates that the coordinated development of advanced manufacturing cluster in Beijing–Tianjin–Hebei region is increasing. The coordination degree of adjacent base periods fluctuates, which indicates that the level of cooperation between subsystems is not stable in a continuous period of time.

Through the comprehensive analysis of the calculation results of the two methods, although the linear weighted average method and the geometric average method are different in the mean and data fluctuation characteristics, they are highly consistent in the trend description of the overall synergy degree.

Table 4 The subsystem order degree and composite system synergy degree of geometric average method

Year	Subsystem order degree				Composite system coordination degree	
	Quantity	Quality	Efficiency	Value	Same base period	Adjacent base period
2013	0.3353	0.3447	0.2375	0.0137	-	-
2014	0.3708	0.3836	0.1962	0.0230	-0.0270	-0.0270
2015	0.4424	0.3771	0.1924	0.0558	-0.0507	-0.0155
2016	0.4717	0.3716	0.2080	0.0735	-0.0504	-0.0145
2017	0.4563	0.3703	0.1674	0.0945	-0.0647	-0.0114
2018	0.5272	0.3882	0.2300	0.1137	-0.0500	0.0351
2019	0.5873	0.4571	0.2478	0.1462	0.0789	0.0393
2020	0.7599	0.5155	0.3265	0.2004	0.1863	0.0810
2021	0.8108	0.5626	0.4680	0.2756	0.2812	0.0711
2022	0.8287	0.5396	0.7118	0.4269	0.3705	-0.0624
2023	0.8143	0.5661	0.8029	0.8451	0.4725	-0.0617

4.2.2 Comparative analysis

Adjacent-period analysis of Beijing–Tianjin–Hebei advanced manufacturing cluster coordinated development is susceptible to short-term factors like external environments and policy adjustments, thus affecting judgments of the real coordination state. To eliminate interference, enhance reliability, and reveal long-term evolution trends of regional synergy degree, the same base-period synergy degree is selected for in-depth analysis.

In order to compare the difference between the linear weighted average method and the geometric average method in measuring the synergy degree of the advanced manufacturing cluster composite system in Beijing, Tianjin and Hebei, this part presents the statistical analysis results of the two methods in different regions in the form of box line diagram (Fig. 3), and visually shows the performance of the two methods in terms of mean value and dispersion degree through the box line diagram.

It can be seen from Fig. 3 that the mean value of the linear weighted average method is close to the mean value of the geometric average method, indicating that the difference between the two methods is reduced from the perspective of the region as a whole. In terms of dispersion, the linear weighted average method has a longer box and a large span of whiskers, indicating that when the linear weighted average method is used, the fluctuation of the synergy degree data is more obvious, while the geometric average method data is relatively concentrated, showing better stability.

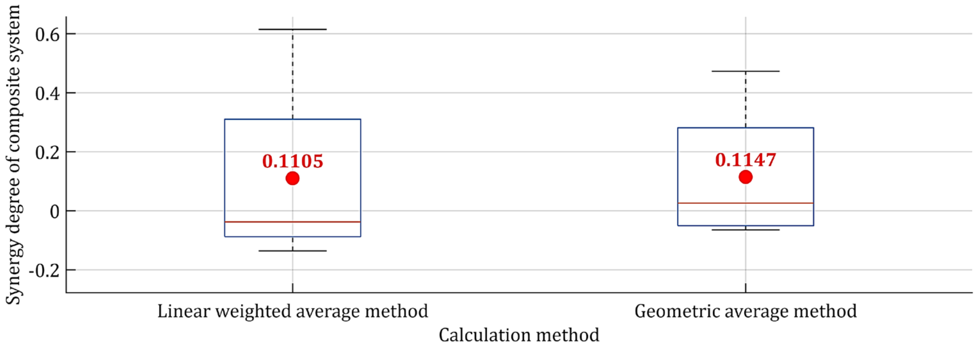

Fig. 3 Box line diagram analysis

4.2.3 Coupling coordination degree model

Combined with the previous comparative analysis of the linear weighted average method and the geometric average method, because the geometric average method performs better in data stability and can more reliably reflect the real trend of coordinated development, according to the above-mentioned Beijing–Tianjin–Hebei advanced manufacturing cluster. The calculation results of the synergy degree of the composite system, based on the synergy degree under the geometric average method, are substituted into Eqs. 14 to 16 to calculate the coupling degree of the cluster's coordinated development, and Fig. 4 is obtained.

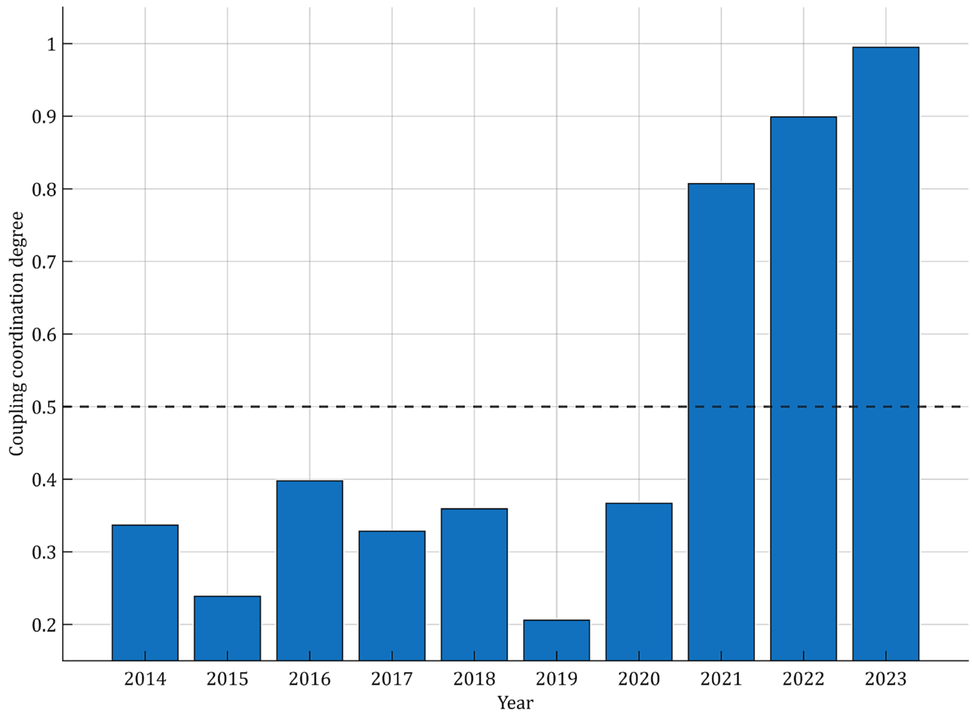

Fig. 4 Beijing-Tianjin-Hebei coupling coordination degree

In Fig. 4, the coupling coordination degree of the Beijing–Tianjin–Hebei cluster presents a 'V-shaped' development trajectory: in 2014-2020, the coupling coordination degree of the cluster was in a state of imbalance, and fell to a low point in 2019. In 2021-2023, the coupling coordination degree rises rapidly, and finally reaches the development level of high-quality coupling in 2023. In general, although there are fluctuations in individual periods, from the long-term trend since 2013, the coordinated development of advanced manufacturing clusters in Beijing–Tianjin–Hebei has shown an upward trend, reflecting the gradual optimization of its resource allocation and cooperation mechanism, and the level of coordinated development of Beijing–Tianjin–Hebei clusters has been continuously improved [30].

4.3 Obstacle degree model

The 16 indicators are selected in the evaluation index system constructed above to calculate the obstacle degree, and calculates the obstacle factors that hinder the coordination of advanced manufacturing clusters in Beijing–Tianjin–Hebei through Eq. 17. The results are shown in Fig. 5.

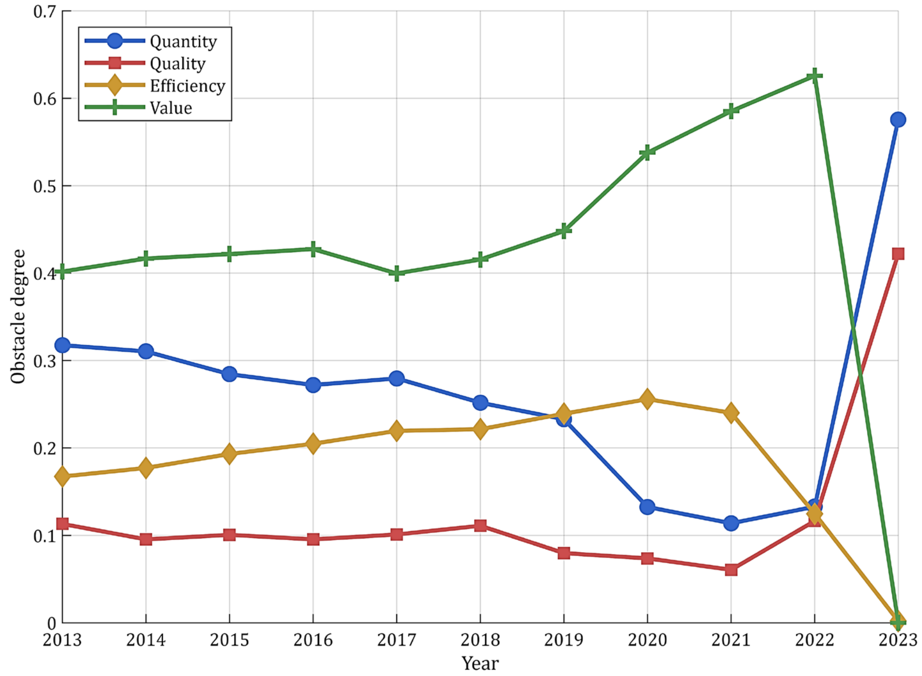

Fig. 5 Trend of obstacle degree of each dimension

Based on the calculation results, in the development process of Beijing–Tianjin–Hebei advanced manufacturing cluster, the obstacle degree of different dimensions shows different trends at different stages.

- The obstacle degree for the quantitative dimension showed a declining trend from 2013 to 2021, reflecting a weakening hindrance to coordinated development. However, from 2022 to 2023, it increased sharply, becoming the primary obstacle to synergy within the Beijing–Tianjin–Hebei advanced manufacturing cluster by 2023. This suggests that the quantitative dimension has emerged as a new development bottleneck.
- A trend similar to the quantitative dimension is observed, with the obstacle degree rising volatility from 0.1132 in 2013 to 0.4222 in 2023. This indicates that declining patent quality increasingly constrains regional synergy.
- The efficiency obstacle degree increased consistently from 2013 to 2020, pointing to a growing constraint from the efficiency dimension. After 2020, however, sustained improvement was observed.
- From 2013 to 2022, the value obstacle degree fluctuated upward and consistently represented the largest proportion among all dimensions, highlighting the value dimension as the principal shortfall in cluster coordination. Optimization began after 2022, and by 2023 its obstacle degree had dropped to the lowest level.

In summary, the coordinated development of advanced manufacturing clusters in Beijing–Tianjin–Hebei from 2013 to 2023 is affected by the interweaving of multi-dimensional obstacles. The dynamic changes of the obstacles in each dimension reflect the complex challenges faced by the coordinated development of the industry. In the follow-up, it is necessary to accurately implement policies to break the bottleneck and promote the coordinated high-quality development of the cluster according to the stage characteristics of the obstacles in different dimensions.

5. Conclusions and implications

The integration of patent indices with the synergy degree and coupling coordination degree models is confirmed to provide a universal analytical framework for assessing the collaborative evolution of advanced manufacturing systems. This approach systematically captures dynamic patterns and development bottlenecks in regional industrial cluster synergy. Empirical analysis of the Beijing–Tianjin–Hebei advanced manufacturing cluster reveals long-term improvement in coordination despite short-term fluctuations, reflecting a transition from disordered to ordered development, with internal subsystems achieving high-quality coordination.

However, key constraints on synergy are identified through the obstacle degree model, including structural risks in innovation momentum, inadequate mechanisms for patent value realization, and the need to strengthen resource allocation and transformation efficiency. The cluster should focus on building an integrated patent collaboration ecosystem. This can be achieved by implementing patent navigation and high-value patent portfolios, establishing regional patent sharing and transformation platforms, and developing joint patent navigation programs to optimize the allocation of innovation resources.

The proposed framework demonstrates high universality and transferability, enabling application to industrial regions and advanced manufacturing clusters globally for evaluating innovation-driven manufacturing progress and diagnosing synergy barriers. Adopting this patent-based perspective supports the establishment of patent cooperation mechanisms, fostering shared technical standards and patent pools. These measures are expected to advance technology integration and collaborative development within and between clusters, as well as on a global scale.

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